CHAPTER 4

FERRITE POWER TRANSFORMER

4.1 Introduction

Ferrimagnetic oxides, or ferrites as they are usually known, have become available as practical magnetic materials over the course of the last twenty years. During this time, their uses have become established in many branches of communications and electronic engineering and they now embrace a very wide diversity of compositions, properties and applications. In 1909, Hilpert[3] attempted to improve the magnetic properties of magnetic, and in between 1932-1936 Snoek[3] was studying magnetic oxides in Holland;in 1945 he had laid the foundations of the physics and technology of ferrites and a new industry came into being. Ferrites are ceramic materials, dark grey or black in appearance and very hard and brittle.[9]

The applications started in the field of carrier telephone and was extended to domestic television recievers, microwave instrument, computer memory where the combination of good magnetic properties and high resistivity made these materials very suitable as core for inductors and transformers.

The transformers considered in this chapter are those which transmit relatively large powers such that the design is mainly limited by saturation or the heating of the core or windings although the treatment is related to the use of ferrite cores much of it is quite general in its applications.

4.2 Analysis of ferrite transformer

In general , the e.m.f. induced on N turns wound tightly around the magnetic material can be expressed as

$$e = -10^{-8} N A_F \frac{dB}{dt} \quad \text{volts} \qquad (4.1)$$

where A_F is the cross sectional area of core (cm^2)

B is the flux density in line per cm^2

If the flux density B is a sinusoidal, then the induced voltage becomes

$$E = \frac{10^{-8} \omega B_m A_F N}{\sqrt{2}} \quad \text{volts} \qquad (4.2)$$

where E is the induced voltage (volt)

ω is an angular frequency

Assumed that the transformer is lossless, then the primary power is approximatly equal to secondary power.

Therefore,we may write the relation

$$N_p I_p = N_s I_s \qquad (4.3)$$

$$I_p V_p = I_s V_s \qquad (4.4)$$

In practical design, a small size of the power transformer is required. In order to do this, the materials must be chosen as small as possible and the cross sectional area of the ferrite core, A_f must be large enough to produce a fixed flux density, B. Normally, the relation between these parameters and the primary voltage is given by

$$\frac{10^{-8} \omega B_m A_F N_p}{\sqrt{2}} \geq V_p \quad \text{volts} \qquad (4.5)$$

where B_m is the maximum flux density (line per cm^2)

A_F is the cross sectional area of ferrite core (cm^2)

Similarly, when the cross-sectional area of the copper coil, A_{cu} is large enough, and assumed that the total copper coil is formed by a half of primary coil and the secondary coil. For a fixed current density, the current as in the primary wire, i_p may be expressed as.

$$\frac{A_{cu} J}{2N_p} \geq i_p \qquad \text{amperes} \qquad (4.6)$$

If the fluxdensity B is a sinusoidal then

$$B = B_m \sin \omega t \qquad \text{line per cm}^2 \qquad (4.7)$$

Multiplying eqns.(4.5) and (4.6) together, we obtain the relation.

$$\frac{\omega B_m J A_F A_{cu}}{2\sqrt{2}\times 10^8} \geq P_{max} \qquad \text{watts} \qquad (4.8)$$

When the flux density B is a square-wave form, then the equation (4.7) becomes

$$\frac{\omega B_m J A_F A_{cu}}{2\times 10^8} \geq P_{max} \qquad \text{watts} \qquad (4.9)$$

This power constraint is an important condition used for the designer. Normally, the volume of the ferrite and the volume of the copper wire should be as small as possible. The magnetic flux density, B and the electric current density J should be sufficiently high. However, the value of the flux density B can not be raised above the saturation limit, says about 3000 line/cm^2 and the current i can not be so high until it causes an excessive rise in the temperature. These are the limitations of all ferrite materials. Therefore, a high grade ferrite material must be carefully chosen to have a high saturation.

4.3 Ferrite Core loss

A core having magnetic loss may be represented in the form of an impedance as

$$Z = j\omega L_s + R_s \quad \text{ohms} \qquad (4.10)$$

where R_s is the equivalent series loss resistance (ohms)

L_s is the equivalent series inductance (henry)

the equivalent circuit diagram of the impedance in eqn.(4.10) is shown in Fig.4.1

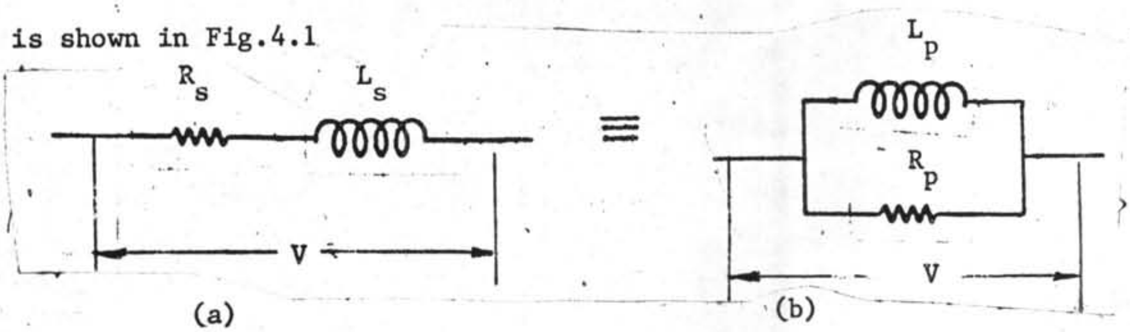

Fig.4.1 An equivalent circuit of the impedance represented magnetic loss

The vector diagrams of Fig.4.1(a),(b) are also illustrated in Fig.4.2

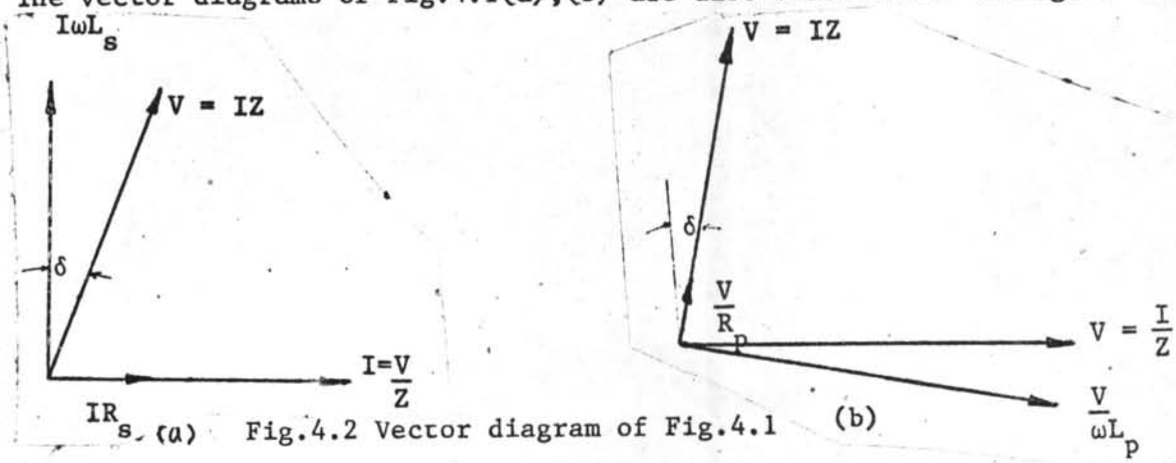

Fig.4.2 Vector diagram of Fig.4.1

It can be seen that an alternative form of the impedance shown in Fig.4.1(b) is the admittanceY, which is

$$Y = \frac{1}{j\omega L_p} + \frac{1}{R_p} \qquad (4.11)$$

From Fig.4.2, it can be seen that the loss tangent can be expressed as

$$\tan \delta_m = \frac{R_s}{\omega L_s} = \frac{\omega L_p}{R_p} \qquad (4.11)$$

Where δm is called the loss angle.

The value of L_p may be expressed by the equation[9]

$$L_p = \frac{\mu_o \mu N^2 A_F}{l_e} \text{ henry} \qquad (4.12)$$

Where μ_o is the permeability of the air (henry/cm^2)

μ is the permeability of a ferrite material (henry/cm^2)

N is number of turns

and l_e is the effective length of the magnetic circuit

By substituting this value of L_p into the eqn(4.11) we obtain

$$\tan \delta_m = \frac{\omega \mu_o \mu N^2 A_F}{R_p l_e} \qquad (4.13)$$

Since the active loss is $\frac{E^2}{R}$ and from the eqn. (4.13), the value of R_p can be calculated by

$$R_p = \frac{\omega \mu_o \mu N^2 A}{l_e \tan\delta_m} \text{ ohms} \qquad (4.14)$$

Therefore, the core loss, P_m will be

$$P_m = \frac{\omega B_m^2 A_F L_e}{\mu_o} \frac{\tan\delta_m}{\mu} \text{ watts} \qquad (4.15)$$

The value of the loss tangent $(\frac{\tan\delta_m}{\mu})$ which can be obtained directly from the graph provided by the manufacture is given in Appendix C

4.4 Copper Loss

The ohmic loss may be expressed in terms of the current density J, the resistivity, ρ (ohm-cm) and the copper volume, V_{cu} (cm^2) as

$$P_\Omega = \rho J^2 V_{cu} \quad \text{watts} \qquad (4.16)$$

This value, P_Ω is the constraint equation which will be used in the example of high frequency ferrite transformer design described in section 4.6

4.5 Core Dimension

The figure of the ferrite core is an E-I type as shown in Fig.4.3

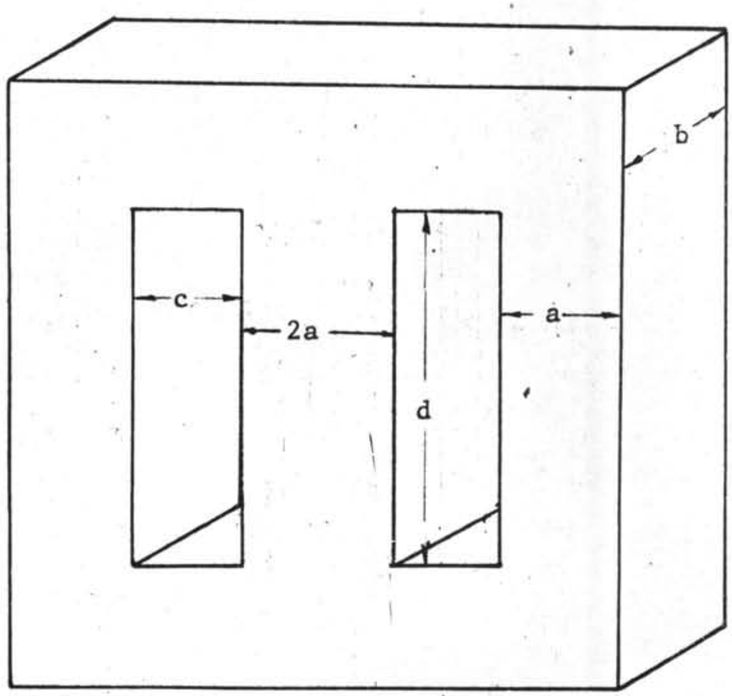

Fig. 4.3 Core dimension

It can be seen that the cross-sectional area of the ferrite core is

$$A_F = ab \quad cm^2 \quad (4.17)$$

and the total area of the window is

$$A_W = cd \quad cm^2 \quad (4.18)$$

However, the cross sectional area of the copper is approximately to A_W, therefore

$$A_{cu} = cd \quad cm^2 \quad (4.19)$$

The approximate volume of the ferrite core may be determined by

$$V_F = L_F A_F \quad cm^3 \quad (4.20)$$

Where L_F is the mean ferrite length expressed as

$$L_F = 2(c+d+2a) \quad cm \quad (4.21)$$

and A_F is the cross-sectional area of the ferrite core.

Similarly, the approximate volume of the copper wire may be determined by

$$V_{cu} = L_{cu} A_{cu} \quad cm^3 \quad (4.22)$$

Where L_{cu} is the mean copper wire length expressed as

$$L_{cu} = 2\pi(2a+c) \quad cm \quad (4.23)$$

and A_{cu} is the cross-sectional area of the copper

4.6 Transformer Loss

In transformer design problem, the most important design parameters are first chosen. In view of the previous sections, these possible design parameters are listed in Table 4.1

These parameters have a decisive influence on design, such as a restriction on dimension in order that the transformer size can be reduced as small as possible.

Table 4.1 List of design parameters.

E_1	E_2	E_3	E_4	E_5
Ferrite volume (cm^2)	Copper volume (cm^2)	Core loss (Watt)	Copper loss (Watt)	Power (Watt)

From eqns. (4.9), (4.17) and (4.18) the power constraint equation can be written in form of the parameters a,b,c,d,B_m,J and ω as

$$\frac{\omega\, B_m\, J\, a\, b\, c\, d}{2\times10^{8}} \geq P_{max} \qquad \text{watts} \qquad (4.24)$$

Similarly, from eqns. (4.15), (4.17) and (4.21) the equation of core loss can be expressed in terms of parameters a,b,c,d,ω,B_m and $\frac{\tan\delta_m}{\mu_{ia}}$ as

$$\frac{2\omega\, B_m^2(c+d+2a)ab}{\mu_o\, 10^{16}}\,\frac{\tan\delta_m}{\mu_{ia}} = P_m \qquad \text{watts} \qquad (4.25)$$

For a guarantee design case, the eqn.(4.25) becomes

$$\frac{2\,\omega\, B_m^2(c+d+2a)\, ab}{\mu_o 10^{+16}}\,\frac{\tan\delta_m}{\mu_{ia}} \leq P_{gm} \qquad \text{watts} \qquad (4.26)$$

Where P_{gm} be a garantee core loss

From eqns. (4.16), (4.19) and (4.23) the ohmic loss can be expressed as

$$2\rho\, J^2 cd\pi(2a+c) = P_{\Omega} \qquad \text{watts} \qquad (4.27)$$

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This value of P_Ω which is used in the design must be higher for guarantee design case. Hence the eqn.(4.27)becomes

$$2\rho J^2 cd \leq P_{g\Omega} \quad \text{watts} \qquad (4.28)$$

where $P_{g\Omega}$ be a guarantee copper loss

The design problem is to minimize the core size and copper wire. By using the weighting factor apply to the geometric programming,[14] we introduce the value of K_1 and K_2 are the positive number which are less than one,and the sum of these values must be one.

Then the objective function will be

$$\text{Optimize } Z = K_1 V_{cu} + K_2 V_F \qquad (4.29)$$

Subject to the inequality constraints given by the following equations

$$\frac{\omega B_m J\ abcd}{2\times 10^8} \geq P_{max} \quad \text{watts} \qquad (4.30)$$

$$\frac{2\omega B_m^2 (2a+b+c)ab\ \tan\delta_m}{\mu\ \mu_o} \leq P_{gm} \quad \text{watts} \qquad (4.31)$$

$$\underline{2\rho J^2 cd(2a+c)\pi} \leq P_{g\Omega} \quad \text{watts} \qquad (4.32)$$

where K_1 and K_2 are the weighting factors.

Normally, the values of the flux density B_m,ω ρ,$\frac{\tan\delta_m}{\mu}$ and μ_o are already known.

Consequently, the parameters a,b,c,d may be determined by the above equations. It can be seen that the problem of the evalution of these parameters is a nonlinear programming. A geometric programming method which has been written in FORTRAN IV (see appendix B) is introduced to solve these parameters.

to solve these parameters.

4.7 Typical design work for ferrite transformer

In this typical design example, the ferrite core transformer has the following specification listed below:

(a) The primary input voltage V_p = 40 Volts

(b) The design regulator output V_o = 5 Volts

(c) The maximum power output, P_o = 50 Watts

(d) The transformer operating frequency, f = 40 KHz

From Fig 3.1, the voltage drop in a diode is about 0.6 Volt and assume that only 70% duty cycle of the switching wave form is encounted. Therefore the approximate design secondary voltage will be

$\left(\frac{5+0.6}{0.7}\right)$ Volts

For a factor of safety in the regulation due to loss in the filter, it is usually to add another two volts to make up for miscellaneous input rectifier and transistor. Therefore the approximate design secondary voltage, V_s becomes 10 Volts

The turn ratio n can be directly determined as

$$n = \frac{V_p}{V_s} = \frac{40}{10} = 4 \qquad (4.33)$$

In addition, the specification of the material used in this design has the following properties.

(a) CORE material (See Appendix C)

Ferrite grade $2C_3$

Core type E-I

Saturation flux density, B_{msat} = 3700 lines/cm

Material loss tangent, $\frac{\tan\delta_m}{\mu}$ 5×10^{-6}

Operating flux density, B = 400 lines/cm

Permeability for core μ 2000

(b) Copper Material

Resistivity, δ at 25°C = $0,0206025\times10^{-6}$ ohms-cm

Current density, J = 290 A/cm^2

(c) The required for the design

Power requirement	>	60 Watt
Garantee core loss	<	10 milliwatt
Garantee coper loss	<	1.5 Watt

From eqns (4.29), (4.30), (4.31) and (4.32) and let $K_1=K_2=0.5$

$$\text{Min } Z = abc + abd + 2a^2b + 2\pi cda + \pi c^2 d$$

Subjected to

$$145.769\, abcd \geqq 60$$

$$.002738\,(abc + abd + 2a^2b) \leqq 0.01$$

$$0.173267\pi(2acd + c^2d) \leqq 1.5$$

$$a,b,c,d \geqq 0$$

The corresponding values of a,b,c, and d will be determined from the digital computer program written in Appendix B. The computation results have given in Appendix B

The optimal values of a,b,c and d obtained from the digital computer are as

a	=	0.884	cm
b	=	0.980	cm
C	=	0.700	cm
d	=	1.699	cm

For practical design, the core type number E-I 1-40 is chosen and dimension is illustratied in Fig 4.4

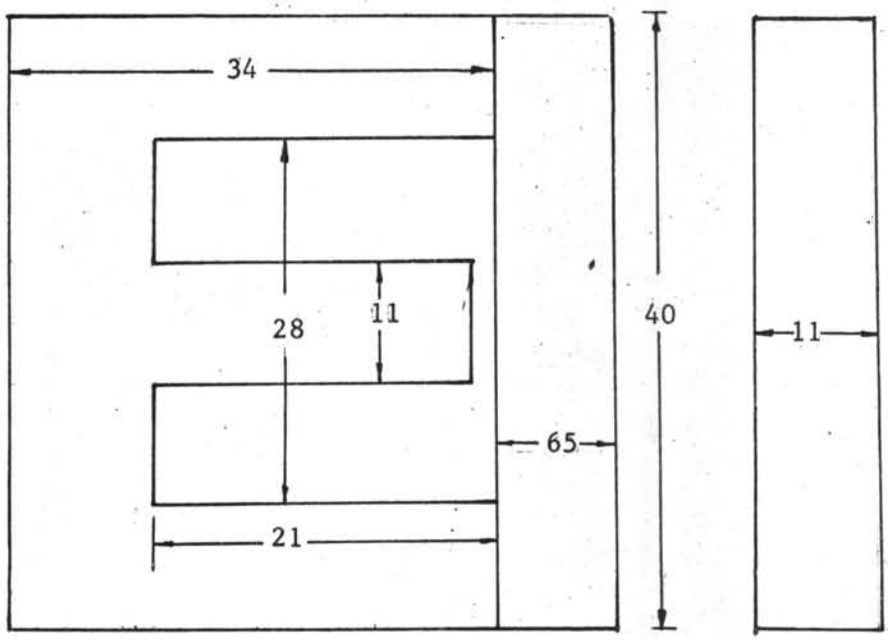

Fig 4.4 Core dimension for 60 Watts power transformer
(Unit in mm.)

The minimum number of primary turn, N_p may be determined by the equation.[5]

$$N_p \geq \frac{10^8 V_p}{4A_F f B_m} \quad \text{turns}$$

The approximate value of the cross sectional area of core is 1 Cm^2

Hence

$$N_p \geq \frac{40\times10^8}{4\times1\times10^3\times4\times3.7\times10^3}$$

$$\geq 7 \text{ turns}$$

This is the minimun number of turns required in the design. For a good coupling, 10 turns are desirable on the secondary. Since the turn ratio is 4:1, the primary turns will be 40 which is higher than N_p = 7 previously determined.

The cross-sectional area of the window using the new value of N_p becomes

$$A_w \geq \frac{(2N_pA_{xp} + 4N_sA_{xs})}{0.8} \quad cm^2$$

Where N_p,N_s are the number of turns of primary and secondary winding respectively A_{xp},A_{xs} are the area of cross-section of copper wires for primary and secondary winding, respectively.

In this case, the wire size number 18 with the cross sectional area 0.82 mm^2 is chosen the primary side and the wire size number 22 with the cross sectional area 0.32 mm^2 for the secondary side. (see appendix E)

$$\text{Hence } A_w \geq \frac{\left(2\times40\times\frac{0.82}{100}+4\times\frac{10\times0.32}{100}\right)}{0.8}$$

$$\geq \frac{(0.656+.128)}{0.8}$$

$$\geq 0.784 \; Cm^2$$

It can be seen that, the core size has the window area A_w = $2.1 \times 0.85 = 1.68\ Cm^2$ and it has sufficient room so that the design is acceptable.